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Bidirectional Reflectance Distribution Function (BRDF)-Based Coarseness Prediction of Textured Metal Surface

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ABSTRACT Because coarseness has a remarkable effect on visual appearance, there has been an increasing demand for measuring quantitative coarseness based on an explicit algorithm, especially in industry. However, even in BYK-mac, a reliable measurement device for high correlation with visual inspection, its results are not clearly defined and not traceable to international standards. In addition, previous studies requiring a captured image of a sample that is sensitive to capturing conditions are not appropriate to apply to industrial sites. Therefore, in this paper, a novel method for predicting coarseness by measuring only the color and the bidirectional reflectance distribution function (BRDF) is presented. The proposed method generates images using illumination optical analysis by applying the BRDF, which is insensitive to the capturing conditions, so it can be reliably applied to industrial sites with various measurement disturbances. The proposed coarseness prediction workflow was verified based on a comparison of the predicted coarseness values of 56 samples with seven levels of roughness for each of the eight colors and the measured values using BYK-mac. Images generated from illumination optical analysis through BRDF of the prepared sample showed lower brightness on the rougher surface, similar to the BRDF measurement results. The results of the measurement and comparison show that the coarseness orders for each color are similar to each other and that the coarseness variations according to roughness levels are also similar, with a coefficient of determination, R^2, of 0.9374.

INDEX TERMS Bidirectional reflectance distribution function, coarseness, texture analysis, textured metal surface.

I. INTRODUCTION

Color is an important factor for increasing the attractiveness of industrial products, such as mobile phones and automobiles. Thus, the implementation of various colors is becoming increasingly important in various industries [1]–[3]. When implementing various colors (also called albedo), maintaining the quality of the color determined by the color of the pigment is crucial. Because esthetic differences occur not only from the color of the pigment but also due to the roughness of the painted surface, it is important to develop a method for measuring the color of a product. In general, when a metallic coating is applied to the exterior of a product, components of visual appearance (VA), such as painted color, coarseness, and glint, are referred to as visual textures [4], [5]. Glint and coarseness are often referred to as sparkle and graininess, respectively. Since these visual textures have a noticeable contribution to VA, studies on the correlation between each visual texture and VA have been reported [5], [6].

BYK-mac (BYK-Gardner GmbH, Geretsried, Germany), which can measure each element simultaneously, is used to quantify visual textures, such as color, glint (sparkle), and coarseness (graininess). For color measurement, BYK-mac illuminates a sample at 45° and then performs a measurement using a spectrometer according to predefined

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angular positions [7]. Visual textures, such as glint and coarseness, can be evaluated through two-dimensional (2D) intensity measured using a monochrome charge coupled device (CCD) by illumination at 15°, 45°, and 75° from the vertical direction on the sample surface. By the way, glint is generally observed under unidirectional illumination conditions. However, the glint characteristic greatly diminishes under the diffused illumination. And only the coarseness characteristic appears in the completely diffused illumination [6]. A diffusion plate must be inserted to measure coarseness, such that diffused light can be illuminated on the sample. Applications in many industries have demonstrated that measurements of visual textures using BYK-mac yield excellent consistency with the visual experiments. Therefore, in related industries, measured data are generally used on each visual texture as a guideline to achieve targeted VA. However, as BYK-mac has its own sparkle and graininess scales and the corresponding measurands are not clearly defined and not traceable to international standards, the National Metrology Institute (NMI) and other companies have not been able to replicate it. Therefore, there is technical difficulty to quantitatively analyze the correlation between visual textures, which have a great effect on VA, and deviation in exterior processing in real products.

It is generally regarded that coarseness has a more dominant effect than glint on the overall VA [8]. Therefore, many studies have attempted to develop a reliable quantitative measurement method of coarseness, comparable to BYK-mac [9]–[12]. Kitaguchi *et al.* used images of metallic coated samples from a digital camera and calculated the sum of amplitude of all frequencies by the Fourier transform on the images to predict coarseness. In this experiment, they used samples coated with 150 types of coating conditions, and they validated their proposed coarseness prediction method by comparing the visual experimental results for the same samples [9]. Ferrero *et al.* obtained graininess images of 25 samples with different achromatic graininess images using an integrating sphere with diffused light illumination. In this experiment, a white ceramic sample image was used as a reference image for reflectance to correct the luminance scale of each image. They presented a model for quantitatively evaluating coarseness by identifying the average luminance factor and the power spectral density of the acquired graininess images [10]. Amookht *et al.* reported quantified coarseness with metallic samples by using 16 samples having two types of color and eight sizes of aluminum flakes. In their study, samples were captured as RGB images using a commercial scanner. To quantify coarseness, they used several methods based on spatial frequency, including the autocorrelation function, the distance-dependent edge frequency, the gray-level co-occurrence matrix, the Fourier transform, and a wavelet transform, and they showed that the results of the proposed spatial frequency-based methods were highly correlated with the results of the visual assessment [11].

Previous studies estimated coarseness using captured images or scanned images of the surfaces of all samples. However, when capturing or scanning the images of the sample surface, there is a probability of non-uniformity of luminance and color between each sample. Therefore, to solve the non-uniformity of luminance and color, one must obtain a reference image in advance for correcting luminance and color. However, in the case where the measurement environment changes (e.g., color temperature, illuminated optical power, and distance to an object from the light source), it is essential to obtain a new reference image. In addition, it is necessary to consider measurement errors that may occur while taking a reference image.

In this study, we proposed a coarseness prediction method based on the measured bidirectional reflectance distribution function (BRDF) data, which is presented as a function of the angle and wavelength of the reflected light flux from the sample surface with roughness. In contrast to previous studies, BRDF can be measured according to the measurement standard with goniometer [12]. It also provides information on the directional characteristics of reflected light flux correlated with incident angles and wavelengths of light. Therefore, compared to the previously studied methods that use images, the proposed method has an advantage that it does not require correction for capturing conditions such as luminance and color. Based on the BRDF and color measurement data, the spatial luminance and colorimetry data based on CIEXYZ, defined by Commission internationale de l'éclairage (CIE), were obtained using illumination analysis software, and the coarseness was predicted based on the calculation of the sum of amplitude of all frequencies by the Fourier transform. The detailed prediction model is described in Section 2. In this study, the coarseness results predicted by the proposed method were compared with the coarseness measurement results from BYK-mac to examine the validity of the predicted coarseness for each sample. As both BRDF and color can be measured relatively easily based on standard conditions, a simple and reliable coarseness prediction method compared to the methods suggested in previous studies is established.

II. METHOD OF COARSENESS PREDICTION FROM MEASURED BRDF

In general, when luminous light flux at a specific wavelength is incident on an optical interface with roughness, BRDF represents the reflectivity at the interface as a function of the light source position and the observation position. In more detail, as shown in (1), the BRDF can be expressed as a multivariable function of the wavelength of the incident light and vectors that define the direction of the light source and the observation position at the interface where the reflection occurs.

$$BRDF\ (\theta_d, \varphi_d, \theta_i, \varphi_i, \lambda) = \frac{dL(\theta_d, \varphi_d, \lambda)}{dE_0(\theta_i, \varphi_i, \lambda)}, \quad (1)$$

where subscripts i and d represent the light source and the receiver, respectively; θ and ϕ are the angle vectors representing the directions of the light source and the receiver located from the optical interface, respectively; $E_0(\theta_i, \phi_i, \lambda)$ is the illuminance in units of [cd·sr·m^{-2}, lux], irradiated to the optical interface from the light source, which can be defined as a coordinate, (θ_i, ϕ_i); $L(\theta_d, \phi_d, \lambda)$ is the luminance in units of [cd·m^{-2}], reflected from the optical interface in the observer direction, which can be defined as a coordinate, (θ_d, ϕ_d); and λ is the wavelength. Therefore, the unit of the BRDF is represented as 1/sr (steradians) by (1) [13]. Measuring the full BRDF is time consuming. Even if the incident and measurement angles are measured in units of 1°, 64,800 points should be measured. If the measurement time becomes longer, events such as fluctuations in the light source output, changes in the sensitivity characteristics of the detector element due to changes in internal temperature, and external mechanical vibrations and shocks may occur. Therefore, several previous studies have performed BRDF measurements that exclude long-term measurements and side effects, with studies being conducted to obtain results similar to full BRDFs with a small number of incident angles. As a result, the BRDF estimation model to which the scattered data interpolation technique is applied has been studied [14], [15]. The scattered data interpolation technique accurately completed the estimated model when it was determined that there was little noise in the data. In our study, for the measurement of BRDF, we used a commercial device, Mini-Diff V2, Light Tec, France. And LightTools^{TM} illumination optical analysis SW we used applies the scattered data interpolation technique introduced earlier to generate a full BRDF from the measured BRDF measurements of four incident angles. From the BRDF, it is possible to calculate the total integrated scattering (TIS), which can be defined as the ratio of the total power generated by all contributions of scattered radiation into the backward half-space to the power of the incident radiation. TIS can be calculated from the BRDF, as expressed by (2).

$$TIS = \int BRDF\,(\theta_d, \varphi_d, \theta_i, \varphi_i, \lambda)\cos(\theta_d)\,d\Omega_\mathrm{d}, \qquad (2)$$

where Ω_d is the solid angle of the reflected light flux [16], [17].

Fig. 1 shows the coarseness prediction flow for calculating the quantified coarseness values from both the BRDF measurement and color measurement data. Fundamentally, the LMS (long, medium, short) color space represents the response of the three types of cones of the human eye. In the proposed prediction method after obtaining the simulated image of the sample, the coarseness is predicted by calculating the sum of amplitude of all frequencies by the Fourier transform of the weighted luminance channel, considering the contrast sensitivity function (CSF) on the CIEXYZ in the LMS. To obtain image in the LMS of the sample, the proposed method requires the calculation of CIEXYZ through illumination simulation based on the measured BRDF and averaged color of the sample. We introduce the actual experimental conditions and simulation method used in our study, and describe each step in the prediction flow.

We prepared 56 samples with seven levels of roughness and eight different colors generated by color-anodized finishes. First, the color of each sample was measured using a colorimeter. Fig. 2 shows the results of the measured color for samples with seven different roughness values for each color when the colors are red, green, blue, and achromatic silver. In Fig. 2, CIELa∗b∗ is a color space designed to numerically represent the color difference between colors in the CIEXYZ color space, considering human perception [18].

It is a color space that is currently standardized worldwide because it expresses colors close to that of the human eye. From the measurement results shown in Fig. 2, for the case of having the same color, the measured color deviation between samples with seven different roughness levels was insignificant. Therefore, the wavelength-dependent reflectance of the color sample was set based on the average color value for each color when calculating the CIEXYZ.

In general, both the wavelength and incident angle of the light flux should be known accurately for measuring BRDF.

Therefore, a collimated light flux incident onto the optical interface with several incidence angles was used in the BRDF measurement. To measure BRDF covering all visible wave spectra, monochromatic light sources with wavelengths of 630 nm (red), 525 nm (green), and 465 nm (blue) were used. During measurement of BRDF, the luminance, L, of the reflected light flux from the circular area with a diameter of 1 mm on the optical interface was measured at all angles of reflected light flux for each angle of incidence. Fig. 3 shows the measured BRDF for vertical illumination, $\theta_i = 0, \phi_i = 0$, of two samples of the same color, silver, with different levels of roughness.

As shown in Fig. 3, the reflectance graph of the sample with lower roughness shows obvious directionality compared to the sample with higher roughness.

In the next step of the workflow, using the measured BRDF and averaged color, it is necessary to calculate the CIEXYZ with spatial luminance through illumination analysis. For this illumination analysis, we used the commercial software LightTools^{TM} (Synopsys Inc., Mountain View, CA, US). As the proposed method replaced the real measurement of coarseness with illumination analysis using measurement data of BRDF and color, it was necessary to establish a simulation model similar to the setup for real measurement. Therefore, in the illumination analysis, the simulation model was configured with the same setup as the setup for measuring the coarseness with BYK-mac, as shown in Fig. 4. We noted that the coarseness of human vision assessment is significantly affected by the reflective properties of surface roughness, which is well defined by the BRDF. Therefore, our study generates a sample model with key properties of the real sample. For this purpose, we applied both measured BRDF and measured color as optical properties of the sample model. We called this sample the "approximated sample".

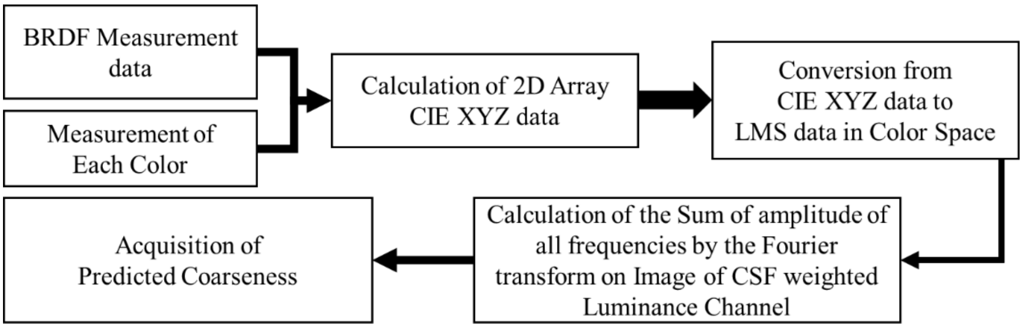

FIGURE 1. Workflow of coarseness prediction.

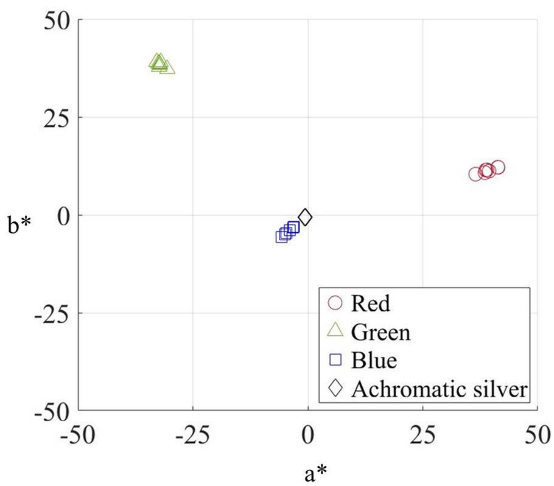

FIGURE 2. Example of measured color coordinates of samples in four types of color with different levels (Lv.) of roughness. In the graph, the x-axis and y-axis represent a∗ and b∗ of CIELa∗b∗ coordinates. In the graph, information on the samples has been presented using four colors, red, green, blue, and silver, with seven different roughness values. The samples are shown in Fig. 5.

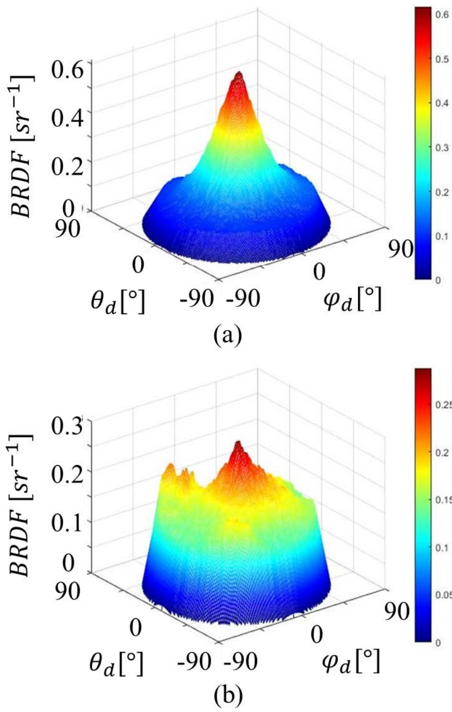

FIGURE 3. Measured BRDF for two samples in the same color, silver, with (a) lower level of roughness, and (b) higher level of roughness.

The analysis model of LightTools™ considers three factors: light source, receiver, and sample. Referring to the actual setup in BYK-mac, we used D65 with a color temperature of 6504 K as a light source, as defined by the CIE.

In addition, because BYK-mac applies diffused illumination to measure the coarseness, in the simulation model, incident light flux from the light source was diffused after it passed the diffusive material, and it was illuminated onto the optical interface. The receiver in the analysis model was placed in the direction perpendicular to the object surface, and the viewing angle of the receiver was set to 10°, according to the measurement conditions of BYK-mac [9]. Finally, according to the averaged color information of the measured sample, the reflectance with respect to wavelength was set individually for each sample, and then the analysis was performed. If illumination analysis is performed based on the settings described above, CIEXYZ with spatial luminance can be obtained from the receiver.

From previous studies, it is generally known that diffuse coarseness, which induces a difference in VA, can be regarded as the perceived contrast in the light/dark irregular pattern exhibited by effect coatings viewed under diffuse illumination conditions [6], [9]. CIEXYZ coordinates, which are tristimulus values, represent the colors perceived by humans as coordinates. In the CIEXYZ coordinates, as the Y coordinate contains information of the greenish color stimulus, as well as of the luminance level, color information cannot be completely excluded in the CIEXYZ color space.

In contrast, in the LMS color coordinate system, it is possible to separate the luminance, red-green, and blue-yellow channels [19]. Therefore, luminance level information can be extracted by converting the CIEXYZ data into color space LMS data. Equation (3) shows the conversion relation from XYZ color coordinates to LMS color coordinates. In (3), the luminance channel (LC), red-green channel, and yellow-blue channel can be defined as $L+M$, $L/(L+M)$, and $S/(L+M)$, respectively [12]. the sum of amplitude of all frequencies by the Fourier transform calculated from LC

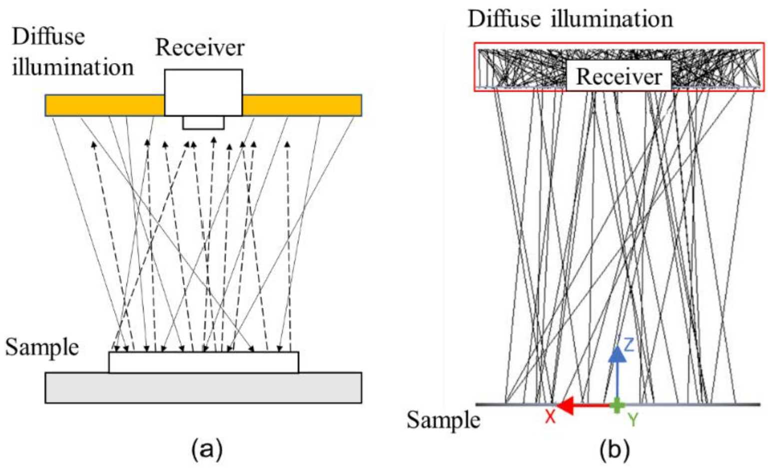

FIGURE 4. Conceptual diagram of (a) coarseness measurement with BYK-mac, and (b) the simulation model in LightTools^{TM}, constructed following the measurement setup in BYK-mac.

data can be approximated as a contrast value resulting from the coarseness of the optical interface. To remove the dc component from the LC data in the image, we generate LC_{var} by subtracting the average value of LC [9].

$$\begin{aligned} L &= 0.236157X + 0.826427Y - 0.045710Z, \\ M &= -0.431117X + 1.206922Y + 0.090020Z, \\ S &= 0.040557X - 0.019683Y + 0.486195Z. \end{aligned} \tag{3}$$

In addition, LC_{DFT}, which represents the contrast value for each spatial frequency, can be generated by computing the 2D discrete Fourier transform (DFT) of LC_{var}. Since coarseness is a value that is perceived by human vision, it is necessary to apply the weight according to the spatial frequency to LC_{DFT}.

In this study, the sum of amplitude of all frequencies by the Fourier transform was calculated by multiplying the intensity weight according to spatial frequency considering the CSF defined by Westland [20]. The CSF is defined as

$$\begin{aligned} CSF\,(u) &= F_L F_c \times 0.28u \exp(-0.3u) \\ &\quad \times \left[1 + \exp(0.3u)\right]^{0.5}, \\ where\ F_L &= \left\{ \begin{array}{cc} 1000(LC_{avg}/70)^{1/3} & if\ 1 \le LC_{avg} \le 70 \\ 1000\left(1/70\right)^{1/3} & if\ LC_{avg} < 1 \\ 1000 & if\ 70 < LC_{avg} \end{array} \right\}, \\ F_c &= 1 - d, \\ d &= \left[(x - x_{white})^2 + (y - y_{white})^2\right]^{0.5}. \end{aligned} \tag{4}$$

In (4), u is the spatial frequency in units of [cycles/degree]; and LC_{avg} is the average luminance level of LC data in the pixel by pixel in units of [cd/m^2]. In addition, d is the chromatic distance from the chromaticity of the white point (x_{white}, y_{white}) to the chromaticity (x, y) of each pixel in the CIEXYZ. To predict the resultant coarseness value, following the calculation formula presented in [9], we slightly modified the predicted coarseness formula to compensate for the difference in luminance between each sample and dividing by the TIS of each sample, as expressed by (5).

$$Predicted\ Coarseness = \log_{10}\left(\sum_{0}^{u_{max}} \frac{LC_{DFT}(u) \times CSF(u)}{LC_{avg} \times TIS}\right), \tag{5}$$

where u_{max} is the maximum spatial frequency of LC_{DFT}.

III. EXPERIMENTAL RESULTS AND PREDICTION RESULTS

In this study, as shown in Fig. 5(a), we used samples with seven levels of roughness and eight anodized colors. Those samples are not made with the effect coating or diffuse paints. According to the MIL-A-21380B military specification on abrasive materials and the ANSI B74.12-1982, specification for the size of abrasive grains, samples with seven different levels were fabricated in the order of 12, 16, 24, 36, 46, 60, and 80 grit. Generally, a sample with a lower grit value has a higher roughness. We labeled the largest grit as roughness level 1 because it has the lowest roughness, and the smallest grit at roughness level 7 as it had the highest roughness based on the grit number. In this study, we did not apply effect coating on all samples to analyze the effect of roughness alone on the coarseness. In addition, Mini-Diff V2 (Light Tec Inc.) and BYK-mac (BYK-Gardner) were used for BRDF measurement and roughness and color measurement, respectively, and the measurement results were applied to illuminance analysis as shown in Fig. 5(b).

We measured the BRDF for all prepared samples using seven colors with eight different roughness values. During the measurement, light sources that emit at three wavelengths (630 nm, 525 nm, and 465 nm) illuminated the optical interface four times at incidence angles of 0°, 20°, 40°, and 60°. As an example of the BRDF measurement results, Fig. 6 shows the measured BRDFs of red-colored anodized samples corresponding to four angles of incidence along the range of θ_d from −75° to 75° and ϕ_d at 0°.

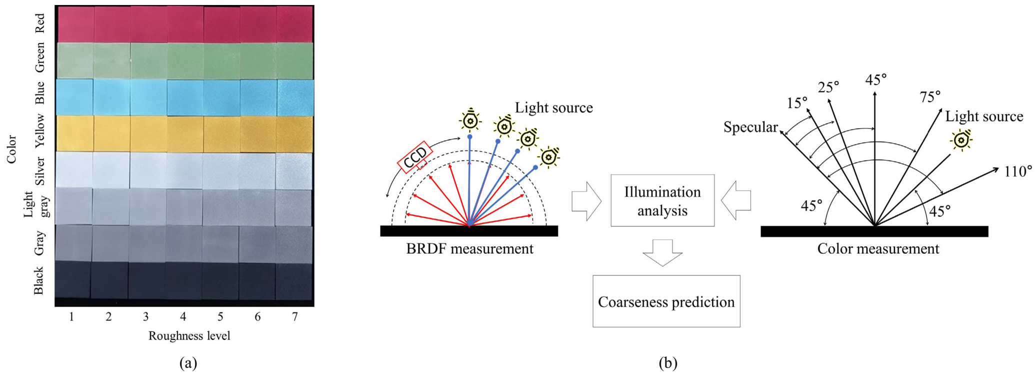

FIGURE 5. **(a) Samples with seven levels of roughness and eight anodized colors (each sample is 5 cm × 5 cm in size). Roughness increases from left to right. (b) The measurement device structure of Mini-Diff V2 for BRDF (left) and BYK-mac for color and coarseness (right). The BRDF is measured with incidence angle of 0°, 20°, 40° and 60°, and collected reflected light flux θ_d from −75° to 75° and ϕ_d at 0°. And the color is measured at the 15°, 25°, 45°, 75° and 110° from the specular reflection with the light source fixed. But for coarseness measurement, the diffused light source is used. Each measurement result is used for illumination analysis. BRDF data is used to represent the surface reflection property, and the color data is used to represent the reflectance with wavelength. Through illumination analysis, the LC image is obtained. By using that image, we can predict the coarseness. This flow is shown detailed in Fig. 1.**

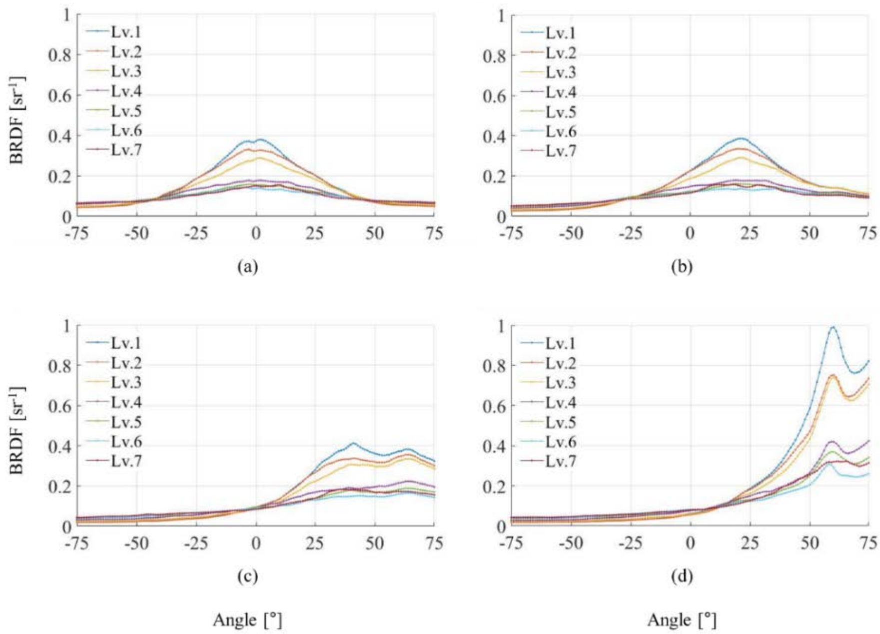

FIGURE 6. **Measured BRDFs of seven samples, color anodized in red, for various angles of incidence. (a) 0°, (b) 20°, (c) 40°, and (d) 60°. In the graphs, the x-axis represents the angle of detection, θ_d. In each figure, the seven lines are the BRDFs corresponding to samples with seven levels of roughness.**

The LC images were arranged in a grid form, as shown in Fig. 7, where each row and column represent the roughness level and color, respectively. In addition, Table 1 shows LC_{avg}, which is the average value of the luminance channel images required for calculating the resultant coarseness prediction. Two prominent features can be observed in Fig. 7 and Table 1.

First, when comparing each color sample based on the same roughness level, we note that a difference in brightness between simulated images occurs because of the difference in basic reflectance between colors. As described above, when the simulation is performed, this effect is observed in the simulated image because the reflectance is defined based on the measured average color information. The second characteristic is that the LC_{avg} value decreases as the roughness increases. This is because the size of the BRDF according to θ_d and ϕ_d is small at high roughness levels where scattering occurs.

Following the simulation conditions discussed in Section 2, we performed a coarseness prediction analysis using the measured BRDFs. Fig. 8 compares the predicted coarseness values through analysis with the BYK-mac measurement results, which are highly correlated with the visual experiment. First, in Fig. 8(a), the coarseness value measured by BYK-mac varies according to the roughness level of the sample and the color. Because the sample with a higher

TABLE 1. **Calculated LC_{avg} from simulated images of each sample.**

Roughness level	Color							
	Red	Green	Blue	Yellow	Silver	Light gray	Gray	Black
1	17.55	37.63	3.56	60.01	43.83	42.70	27.60	4.63
2	16.81	35.23	3.45	58.89	42.87	41.33	25.25	4.81
3	14.70	34.55	3.51	55.91	41.26	40.56	26.92	4.99
4	13.12	31.39	3.12	53.39	35.99	35.34	22.26	4.11
5	8.90	28.03	2.76	51.54	29.97	33.75	20.31	3.86
6	8.23	26.03	2.63	47.42	22.01	31.20	18.80	3.51
7	8.07	25.77	2.54	43.60	21.12	30.36	18.63	3.62

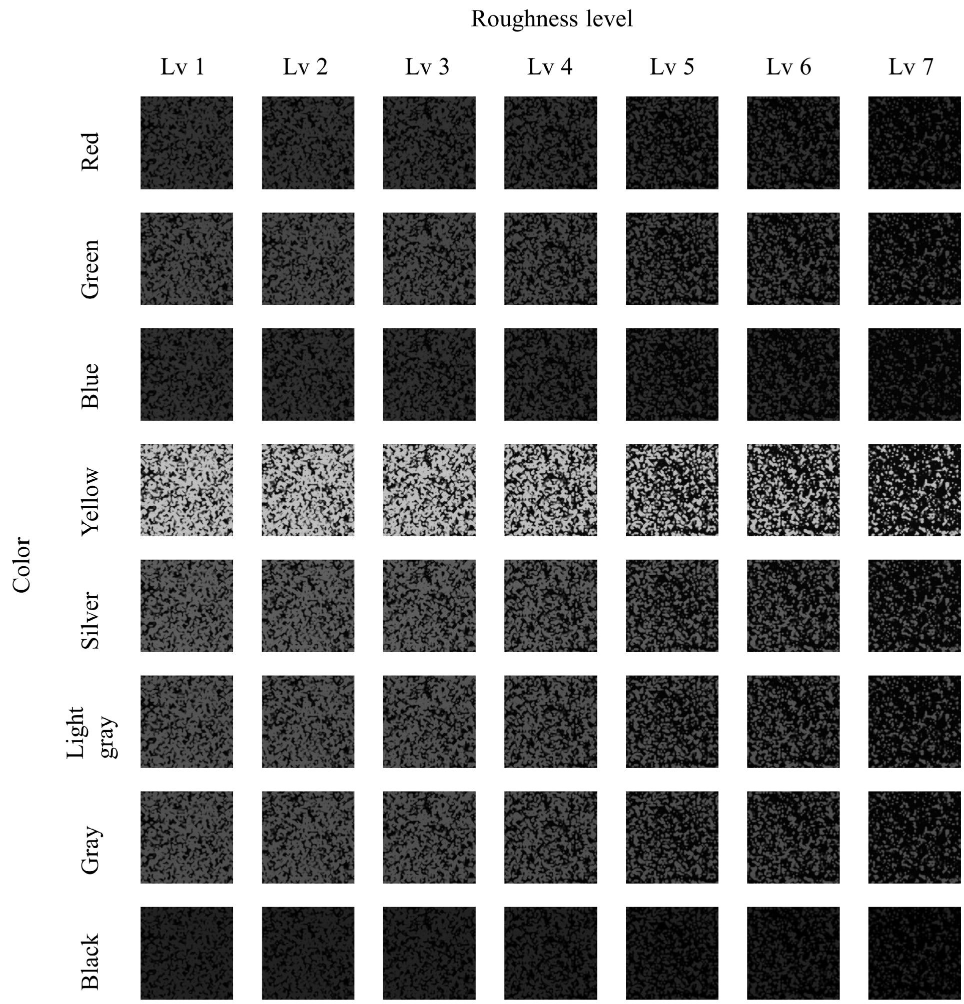

FIGURE 7. **Simulated images from the illumination analysis using LightTools^{TM} on 56 samples.**

roughness level has a larger grain size on the optical interface, it yields a higher value of coarseness, similar to the tendency of the measured BRDF. In addition, a comparison of the coarseness measurement results for each color reveals that the coarseness values of the black, blue, and red colors are low.

This is because the reflectance of these colors is relatively low compared to that of other colors. The magnitude of the coarseness varies according to the color as yellow, silver, green, light gray, gray, red, blue, and black, in the order from the color with the largest coarseness to the smallest. From the data in Fig. 8(b), we note that this order is similar to

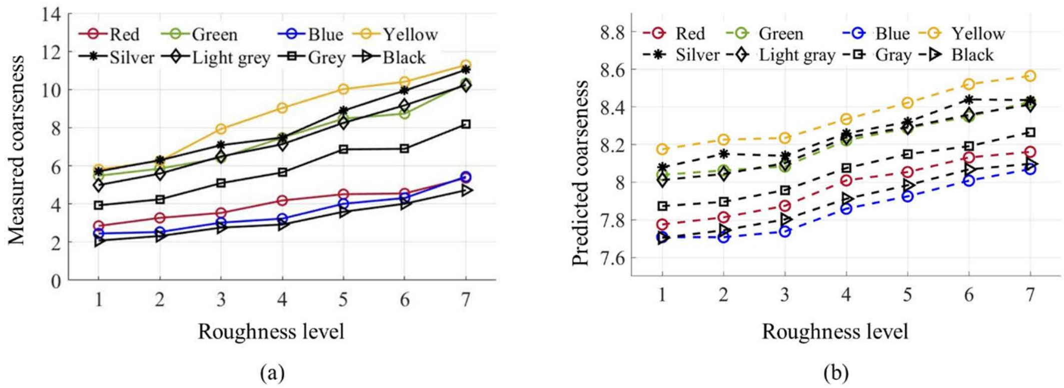

FIGURE 8. (a) Results of measured coarseness by BYK-mac, and (b) results of predicted coarseness value. In each graph, the x-axis indicates the level of roughness, and the color in the graphs matches the color of the sample.

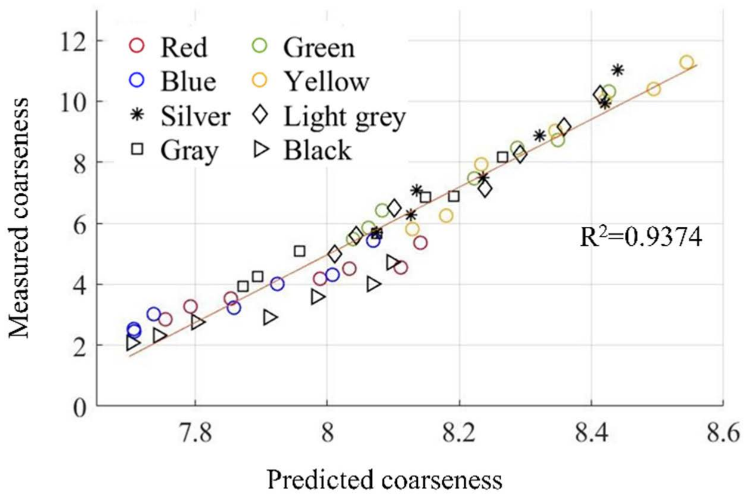

FIGURE 9. Correlation between predicted coarseness based on BRDF data and measured coarseness with BYK-mac.

that of the predicted coarseness values. In detail, as shown in Fig. 8(b), for the predicted coarseness values, the color can be ordered as yellow, silver, green, light gray, gray, red, black, and blue, from the color that yields the largest coarseness. There is a slight difference from the results of BYK-mac in the order of colors according to coarseness prediction values, such as black having a larger value than blue. However, in both the BYK-mac measurement results and the prediction results, the coarseness value offsets between these colors were small. Therefore, the values predicted in this study agree well with the BYK-mac measured values, considering similar tendencies in color and roughness levels.

Fig. 9 shows the correlation between the predicted coarseness values, shown in Fig. 8 (b), and BYK-mac measurement results, shown in Fig. 8 (a), for a total of 56 samples with seven levels of roughness for each of the eight colors. The coefficient of determination (R^2) between the two datasets was calculated as 0.9374. Through correlation analysis, we determine that, regardless of the color and roughness level of the sample, the predicted coarseness values based on the proposed method have a high correlation with the BYK-mac measurement results. As mentioned in the Introduction, as the coarseness measurement value of BYK-mac is generally known to have a high correlation with the visual experiment results, we estimated that the results of the proposed method are also sufficiently correlated with the visual experiment.

In the industry, there is a continuous need to analyze visual texture through an image that accurately expresses the surface. To meet these needs, previous studies proposed image processing technics, for example, synthesizing high-dynamic range (HDR) images with several LDR (low-dynamic-range) images, or image synthesizing techniques using images of a stereo capture system that mimics human eyes. These technics were able to extract surface features well. Since surface features can be clearly extracted from images obtained in proposed research process, it can be sufficiently applied to various methodologies that extract visual textures from images. As well, in this study, we analyzed the images that obtained with illumination analysis by Fourier transform. Obviously, the high-resolution image contains more information than low-resolution image, so it can be analyzed in detail. Therefore, if resolution enhancement is performed using a super-resolution technique such as SISR or MSFFN [21], [22], which has been recently studied, it is expected that the accuracy of this study will be improved.

IV. CONCLUSION

Considering the growing importance of the VA of goods in a wide range of industries, high-accuracy measurements of visual textures, which have a major impact on VA, are becoming increasingly important. In this study, a new method for predicting coarseness, which has a large effect on VA among visual textures, was presented and verified. The proposed coarseness prediction model fundamentally uses the colors and the BRDF which is insensitive to the capturing conditions for the optical interface of the samples, so it can be reliably applied to industrial sites with various measurement disturbances. In the proposed workflow of coarseness prediction, the 2D spatial luminance was calculated using LightTools^{TM}. Finally, coarseness was predicted based on the calculation the sum of amplitude of all frequencies by the Fourier transform. A highlight of the proposed method is that coarseness can be predicted using only color and BRDF measurement values for which measurement conditions are standardized.

To verify the proposed workflow of coarseness prediction, we tested total 56 samples that is composed of seven levels of roughness for each of the eight colors. As a result of the BRDF measurement of all samples, it was found that, for each color, increasing roughness showed very similar tendency for scattering to increase. This indicates that the directionality of the reflected light flux decreases as the level of roughness increases regardless of the incident angle of the illumination during BRDF measurement. In the case of the sample in red shown as an example of this general tendency for all colored samples, for an illumination incident angle of 0°, roughness level 1 has BRDF value of 0.4, but roughness level 7 showed 0.16. Also, the simulated images, or can be also defined as 2D spatial luminance, which are calculated with LightTools^{TM} based on measured BRDF data and color value has the similar trend with BRDF measurement. And looking at the average LC_{avg} values of all colors, shown in Table 1, for each color, a common tendency that the value of LC_{avg} decreases as the roughness of the sample increases can be confirmed. There is a difference in the averaged LC_{avg} value for each color presented in Table 1, which can be understood to be due to the difference in the basic reflectance of the color. Finally, coarseness was predicted based on the LC_{avg} calculated for each sample and compared with the results measured by BYK mac for the same samples. As a result, as shown in Fig. 8, the coarseness curve predicted for each color has an offset from each other. And it was common for both predicted values and measured values with BYK-mac. Also, a high correlation, the high coefficient of determination value, 0.9374, was confirmed through correlation analysis between the two data. The larger the roughness of the sample, the larger the grain size at the optical interface, accordingly the smaller BRDF and the larger coarseness. Therefore, it is judged that it is sufficiently effective to predict the coarseness using the LC_{avg} value calculated by reflecting the basic brightness information of a color based on the BRDF measurement result, which is sensitively changed according to the roughness. In the end, we determined that the results of the coarseness prediction method presented in this study are also sufficiently correlated with the visual experiment.

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